EVALUATION OF STORM SURGES AROUND THE KOREAN PENINSULA IN PRESENT AND FUTURE CLIMATES

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This study evaluates the storm surge around the Korean Peninsula due to the climate change based on results of a coupled model of surge, wave and tide (SuWAT), which is directly forced by the output sets of the present (1979-2008) and future (2075-2099) climates projected by MRI-AGCM model of the Japan Meteorological Agency. It is found that the intensity and the number of the future typhoons increase around the Korean Peninsula and their tracks move toward the east in comparison with the present tracks. As a consequence, the extreme analysis indicates that the storm surges in the future climate are enforced along the south coasts of the Korean Peninsula, especially. The study represents that the effect of the climate change on the storm surge should be taken into account with the coastal-scale variation.

Keywords: storm surge; climate change; typhoon; the Korean Peninsula

INTRODUCTION

According to recent studies (Bender et al., 2010; Schiermeier, 2010; Woodruff et al., 2013), highly intensified typhoons/hurricanes are expected to increase in number and intensity as a result of global climate change. It is indicated that large-scale variations in the atmosphere are globally projected (Kitoh et al., 2009) and the effect of global climate change on sea surface temperature can highly intensify tropical cyclones (Emanuel, 2005). Those concluded the increase of flooding risks and the acceleration of sea level rise.

Korean Meteorological Administration (KMA, 2011) represents that the Korean Peninsula is on the pathways of typhoons from July to September and the number of the typhoon was 327 from 1904 to 2010, which directly and indirectly affected. KMA reported that three typhoons per year make an effect on the Korean Peninsula, resulting in economic losses of 133 billion dollars per year as well as loss of life. In order to reduce such losses due to the typhoon, therefore, the assessment of present coastal facilities against global climate change should be made along coasts of the Korean Peninsula.

This study examines the present and future storm surges along the Korean Peninsula coasts using outputs of an atmospheric general circulation model (AGCM) with 20 km high-resolution cells under the A1B scenario by Meteorological Research Institute (MRI) and Japan Meteorological Agency (JMA), contributed to the Fifth Assessment Report of Intergovernmental Panel on Climate Change (IPCC AR5). In this study, a series of the storm surge calculations are conducted by directly inputting the data sets of typhoon events, extracted from the AGCM outputs, into a storm surge model. In the storm surge simulations, the three leveled-domains downscaling from 12 km resolution grids to 1.3 km high-resolution grids are used to cover the East Asia. In order to evaluate the change of storm surges in the present and future climate circumstances, a series of the simulations are carried out for the present climate (1979 ~ 2008) and the future climate (2075 ~ 2099).

DESCRIPTION OF CLIMATE PROJECTION

Because the detailed description is given by Yasuda et al. (2014), we simply descript the climate projection in the present paper. MRI-AGCM developed by MRI/JMA was used to simulate global climate changes in the present and future climates on the global domain with a 20 km resolution mesh. A series of time-slice experiments were originally conducted by MRI/JMA for the three climate periods: 1979-2008 (present climate), 2015-2039 (near future climate) and 2076-2099 (future climate). The different sea surface temperatures (SSTs) in the bottom boundary are employed to each climate condition: the observed SSTs from the UK Met Office Hadley Centre for the present climate experiment and the ensemble mean SSTs from the coupled model intercomparison projection phase 3 multi-model projections of SRES A1B for the future climate one. The typhoon events, which consist of the spatial distributions of 6 hourly wind speeds at 10m height (U_{10}) and sea level pressure (SLP),

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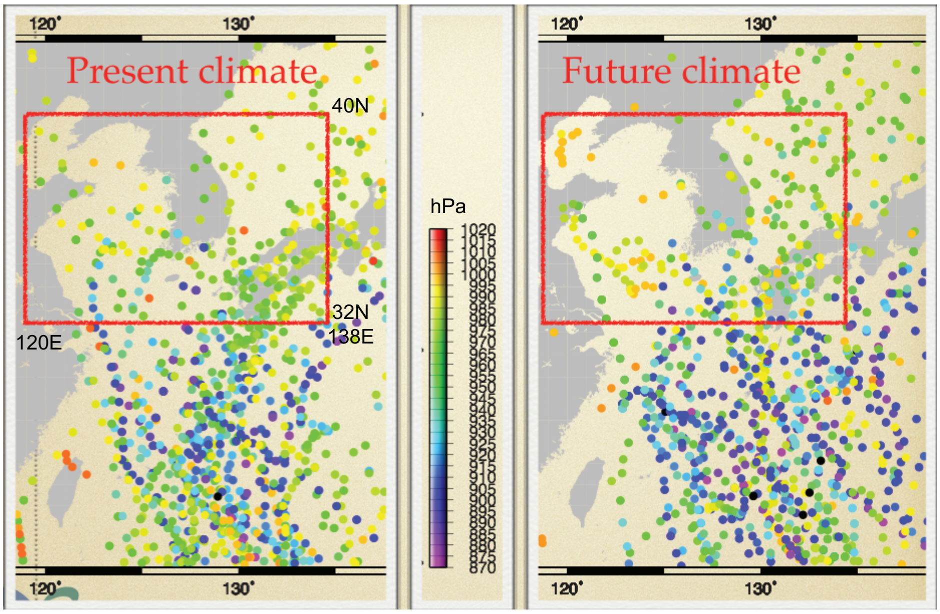
were identified by using the Oouchi et al.'s method (2007) and extracted from the experimental results of the present and future climates. Yasuda et al. (2014) made a comparison of experimental and observed typhoons in terms of tracks, cyclogenesis numbers and central pressures, and concluded that it is appropriate to implement the MRI-AGCM version 3.2S model for extreme storm surges and wind waves. In the present study, we have evaluated the storm surge along the Korean Peninsula during two climates of 1979-2008 (present climate) and 2076-2099 (future climate).

Tropical Cyclone around the Korean Peninsula

Yasuda et al. (2014) indicated that the difference ratio in the number of typhoons is less than ±0.5 per year in the region of 5°-15°N and 140°-160°E in comparing the model results with the best tracks for 1979-2003. In this area, the annual averages of the typhoons from the model and the best tracks are 22 and 26, and the standard deviations are 6 and 4, respectively. The mean values of the central pressure depression are 956.4hPa and 963.4hPa for the model and the best track, respectively. In addition, the difference of the lowest central pressures between the present and future climates is less than 5hPa in the region. It represented that the typhoon will be intensified under the future climate in the North West Pacific.

In the region of 32°-40°N and 120°-138°E, which is defined by the Korean Meteorological Agency as "Korean Peninsula-approach typhoon" (Typhoon White Book, 2011), the numbers of the typhoons are 41 (1.4 per year) and 46 (1.9 per year) for the present and future climates, respectively as shown in Fig. 1, while the historical net number is 3 per year. The annual number of approaching the Korean Peninsula is slightly larger in the future climate than in the present climate. It was found that the typhoon approach increases in the future climate along the Korean Peninsula according to the definition of "Korean Peninsula-approach typhoon". In addition, the figure shows that the modeled tracks are mainly approaching the eastern and southern coasts in the future climate, while those are approaching the western coasts in the present climate. It was seen that the modeled tracks within the defined region shift from the west coasts to the east coasts due to the climate change. We found changes of intensity within the red colored rectangular region, which is highly intensified central pressures (< 920 hPa), appear along the southern and eastern coasts in Korea in the future climate, while those are seen along the western coasts in the present climate. It represents that such changes are caused by the climate change and storm surges should be evaluated to understand the impact of the climate change along the coasts of the Korean Peninsula.



(a) the present climate **(b) the future climate**

Figure 1. Modeled tracks for the present and future climates in the region of 32°-40°N and 120°-138°E. Color indicates the central pressure of typhoons.

Storm surge simulation around the Korean Peninsula

The coupled model of surge, wave and tide (SuWAT) developed by Kim et al. (2008) is used to calculate a storm surge. A series of storm surge simulations was conducted on the multi nested domains downscaling from 12 km grids to 1.3 km grids as shown in Fig. 2, in which the innermost domains of 3rd and 4th domains along the Korean Peninsula coasts are in parallel nested on the 2nd domain. In the simulation, the wave radiation stress and the wave dependent drag coefficients were no taken into account. The tidal impact was also not considered in this calculation for simplicity. The Honda Mitsuyasu relation (1980) was used to estimate the wind stress.

According to the technical summary of the Fifth Assessment Report of Intergovernmental Panel on Climate Change (Stocker et al., 2013), the global mean sea level projections from process-based models for the four Representative Concentration Pathways (RCP) scenarios are in the range of approximately 0.4-0.7m as shown in Figure 3. Those are based on scenarios from four modeling teams and consistent sets of projections except the components of radiative forcing as input for climate modeling. In fact, a local sea level rise should be taken into account and it should be carefully reflected, for example as a time series of sea level rises into the calculation. In the present study, because the aim is to assess the worst storm surges due to the climate change, we decided to use the highest value of the global mean sea level rise from the scenario of RCP8.5 to simplify the calculations. The time mean of 0.6m over 2081-2100 is used for the future climate, which is relative to 1986-2005. In order to consider the effect of the sea level rise, the zero mean sea surface level was implemented into the calculations of the present climate, while the 60cm mean sea surface level was employed to take it into account in the calculations of the future climate.

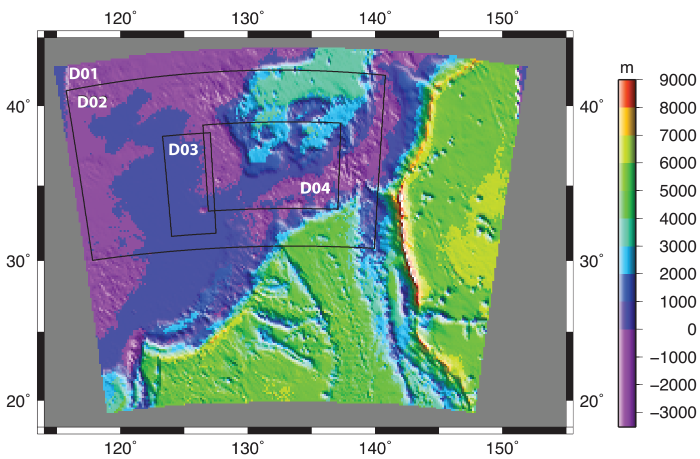


Figure 2. Geophysical regions for storm surge calculations downscaling from 12 km grids to 1.3 km grids.

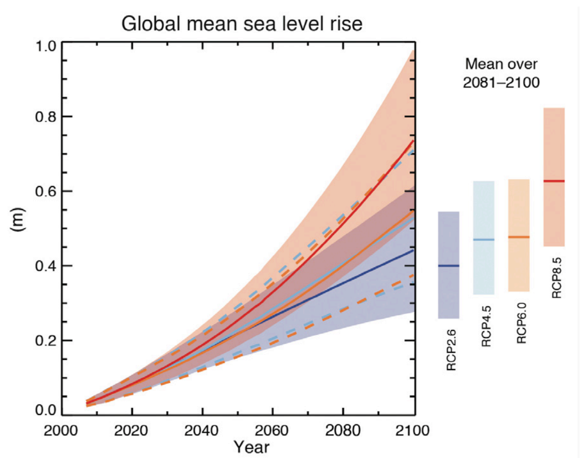
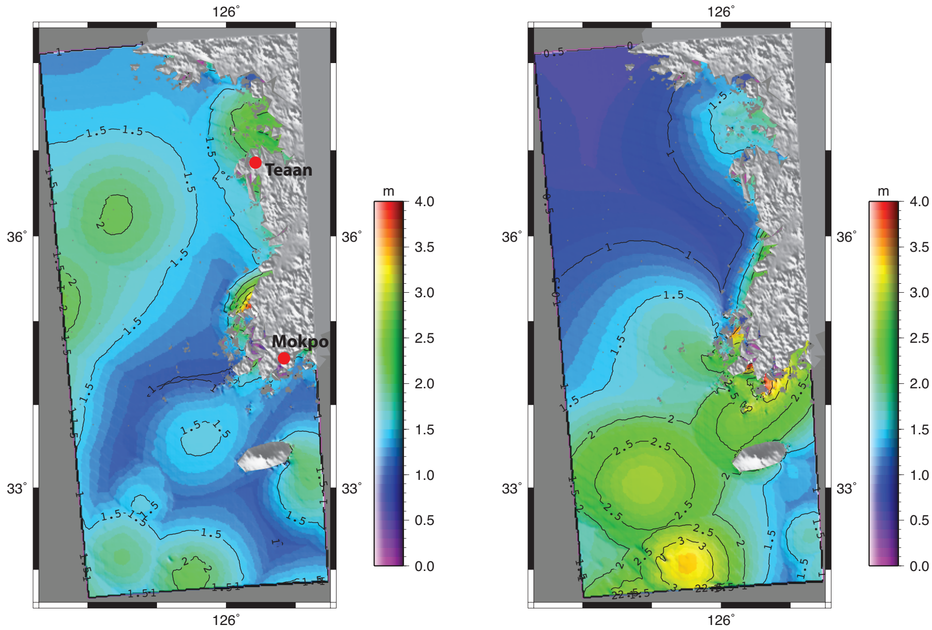


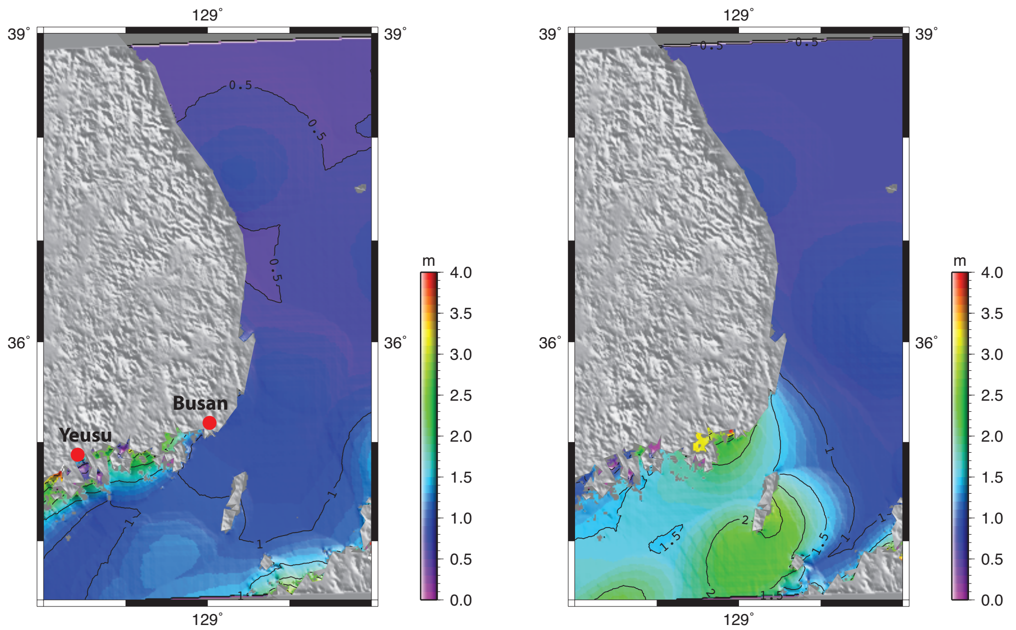
Figure 3. Projections from process-based models of global mean sea level rise relative to 1986-2005 for the four RCP scenarios. The solid lines show the median projections, the dashed lines show the likely ranges for RCP4.5 and RCP6.0, and the shading the likely ranges for RCP2.6 and RCP8.5. The time means for 2081-2100 are shown as coloured vertical bars. (*see* Figure TS.22 in Technical Summary by Stocker et al., 2013)

The 6 hourly data of sea level pressures and winds at 10m, which are obtained from the output sets of the MRI-AGCM version 3.2S model, were directly forced into the SuWAT model. The typhoon events are more than 218 and 270 for the present and future climates, respectively. Each event was forced with the 120h spin-up calculation before calculating the storm surge.



(a) the present climate **(b) the future climate**

Figure 4. The 3rd domain view of highest surge heights along the west coasts of the Korean Peninsula.



(a) the present climate **(b) the future climate**

Figure 5. The 4th domain view of highest surge heights along the south and east coasts.

RESULTS AND DISCUSSION

From a series of the storm surge simulations, we calculated the highest surge heights from the both climates as shown in Figure 4 that the 3rd domain views are seen along the western coasts of the Korean Peninsula. The higher surges (> 2.0m) appear along the west in the present climate, while those are seen at the southwest coast in the future one. The highest surge height is dramatically increased more than 2.5m high near Mokpo. That means that the landfall of severe typhoons may increase along the southwest coasts in the future climate than in the present climate.

Figure 5 represents the 4th domain view of highest surge heights along the south and east coasts for the two climates. In the present climate, the high surges (> 1.5m) intensively occur near Yeusu along the south coasts. On the other hand, those are concentrated near Busan in the future climate and are more than 2.0m. For the east coasts, there are no dramatic changes in the storm surge due to the climate change as found along the west and south coasts. The differences of maximum surge heights (= future – present) are calculated as seen in Figure 6. As a result, the impact of the climate change is apparent on the southwest coasts near Mokpo and on the south coasts near Busan. Their differences are up to 2.0m.

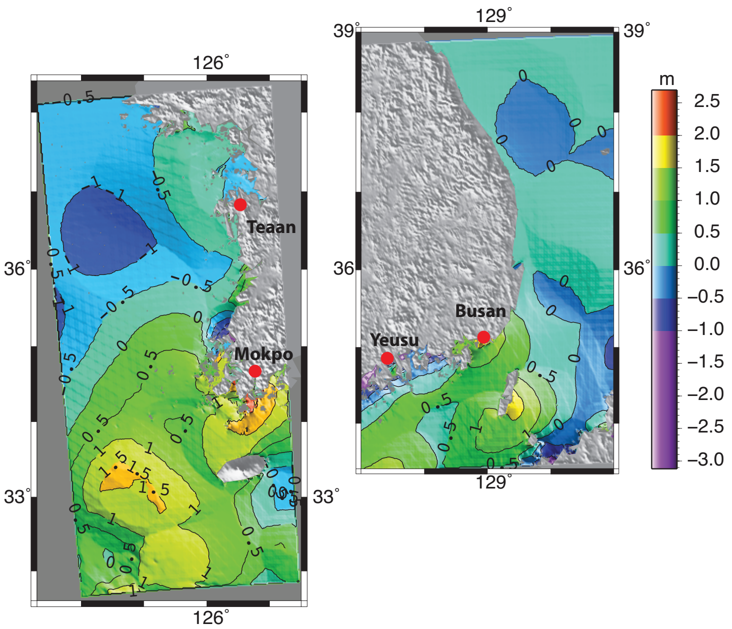
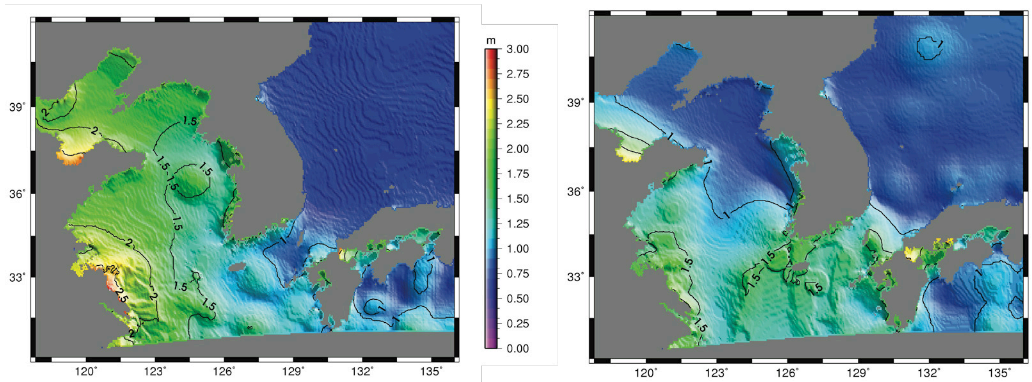


Figure 6. Differences of highest surge heights in the future and present climates (= future – present)



(a) the present climate **(b) the future climate**

Figure 7. Projected maximum surge heights along the Korean Peninsula with the 100 years return period.

From storm surge data sets of the both climates, the extreme surge analysis was conducted to understand surge heights with a return period of 100 years. In the first analysis, the Gumbel distribution was employed to estimate the projected surge heights with the 100 years return period. A little effort is required to estimate a parameter in this distribution because it uses only two parameters of location and scale. To estimate two parameters, the least square method was used. The extreme surge heights are extracted from the time series of calculated surges based on the annual maxima method that the maxima per year are selected. As shown in Figure 7, the 100 years surge heights of more than 1.5m are calculated along the west and south coasts of the Korean Peninsula in the present climate. Especially, the 100 years surge heights are more than 2.5m along the east coasts of China. Such distributions of the

100 years surge heights in the present climate show a change in the distribution of the future surges along the coasts of China and the Korean Peninsula. The 100 years surge heights of more than 2.0m in the present climate along the China coasts are decreased to approximately 1.7m. Such decreases are also confirmed along the coasts in the middle of the Korean Peninsula. On the other hand, the 100 years surge heights of approximately 1.2m are increased to more than 1.5m along the south coasts of the Korean Peninsula in the future climate. Along the east coasts of the Korean Peninsula, the increase in the 100 years surge height is slightly confirmed. From the comparisons of the maximum surge heights and the 100 years surge heights between the present and future climates, it was found that the change of future surges is apparent and its assessment should be done in the local-scale of coasts in the storm surge calculation.

Table 1. K-S test and Anderson Darling test for the projected present and future surge height distributions at four different locations.

	Distribution	Present				Future			
		K-S test		Anderson Darling test		K-S test		Anderson Darling test	
		Statistic	Rank	Statistic	Rank	Statistic	Rank	Statistic	Rank
Mokpo	Frechet	0.0512	2	0.3787	1	0.0456	1	0.1767	1
	GEV	0.1343	5	4.9516	5	0.1237	4	1.6851	4
	GPD	0.1335	4	4.2453	4	0.1161	3	1.5303	3
	Inv. Gaussian	0.0434	1	0.4339	2	0.0725	2	0.3926	2
	Weibull	0.1268	3	3.4827	3	0.3003	5	15.208	5
Teaan	Frechet	0.0419	1	0.268	1	0.0829	5	0.6516	3
	GEV	0.0432	2	0.2735	2	0.0636	3	0.6516	2
	GPD	0.0751	4	4.8862	5	0.0548	1	0.5431	5
	Inv. Gaussian	0.0552	3	0.4859	3	0.0723	4	7.9112	1
	Weibull	0.0888	5	1.8259	4	0.0562	2	0.4484	4
Pusan	Frechet	0.0725	1	1.4796	1	0.0575	2	0.26	2
	GEV	0.0781	2	1.6679	2	0.0561	1	0.2567	1
	GPD	0.1079	4	6.4423	5	0.0668	4	2.402	5
	Inv. Gaussian	0.1048	3	2.6307	3	0.0664	3	0.4907	3
	Weibull	0.1331	5	5.0347	4	0.1202	5	5.0094	4
Yeusu	Frechet	0.1979	4	14.265	4	0.0518	1	0.2272	1
	GEV	0.0747	1	1.7006	1	0.0773	4	0.5177	3
	GPD	0.1081	2	67.113	5	0.0765	3	11.86	5
	Inv. Gaussian	0.2219	5	13.465	3	0.0754	2	0.5078	2
	Weibull	0.1438	3	5.9865	2	0.1027	5	1.6687	4

In addition, the three-parameter extreme distributions of the storm surges for the present and future climates are investigated at the representative coasts around the Korean Peninsula. In this estimation, the peaks-over-threshold (POT) method is used in order to extract the maximum surge height at each event larger than the threshold, which is served to analyze extreme distributions, from the calculated time series of the storm surges at each location. The present study decided to use the threshold, which is the minimum value among the annual maximum surge heights at each location. In the study, we employed the five extreme distributions of Generalized Extreme Value (GEV), Generalized Pareto (GPD), Frechet, Weibull and Inverse Gaussian to the analysis of the storm surge height distribution as shown in APPENDIX. In order to estimate 3 parameters in each distribution, the L moment method was implemented. Then, the distributions are validated by the Goodness-of-fit test of the Kolmogorov Smirnov (K-S) and the Anderson Darling for each climate as listed in Table 1.

In Table 1, the statistic errors for each extreme distribution are given with its rank at four different locations. Then, we investigated a change of the rank how it is altered due to the climate change. In the rank, the first and 2nd ranks are colored with red to highlight them in the table. We examined how a proper extreme distribution in the present climate is changed due to the climate change. The distributions of Frechet and Inverse Gaussian are the best distributions within the 2nd rank at Mokpo and Pusan in the both climates, even though there is a change of the ranks due to the climate change. That means the proper distribution is no change even due to the climate change at Mokpo and Pusan. On the other hand, the projected proper extreme distributions are diverse as the climate is changed at Teaan and Yeusu. For example, while the 1st ranked distribution is GEV at Yeusu in the present climate, it changes to the Frechet distribution in the future climate obtained from two tests. In addition, while the proper extreme distributions make a convergence in the present climate, those are diverse in the future climate, for instance, at Teaan where the 1st ranked distributions are GPD and inverse Gaussian for the tests of K-S and Anderson Darling, respectively. Such results show that there is an uncertainty of the future storm surge projection. Figure 8 shows the appropriate probability density functions (PDFs) in the both climates at four different locations that those are ranked in the first and second from the goodness-of-fit tests. As shown in the figure, it was found that the PDFs move to the right side at Taean, Yeosu and Pusan due to the climate change, while it slightly moves to the left side at Mokpo. Such tendency is proved in the different PDFs of the future climate at all locations. As a result, the study represents that the appropriate PDFs are GEV, Inverse Gaussian and Frechet in the future storm surge distribution. In addition, it was indicated that the PDFs in the both climates depend on the location.

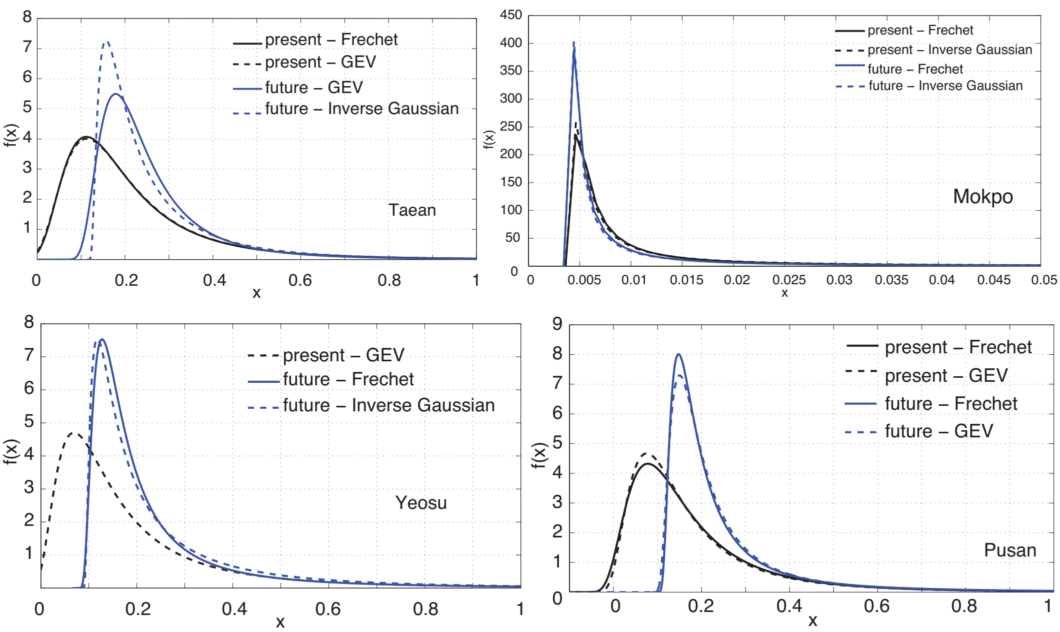


Figure 8. Comparisons of the probability density functions, f(x), for the storm surge in the present and future climates at four different locations.

CONCLUSIONS

In the present study, the effect of the climate change on the storm surge is investigated along the coasts of the Korean Peninsula in using the output sets of the MRI-AGCM model which are directly forced into the coupled model of surge, wave and tide (SuWAT).

From the results of time-slice experiments conducted by MRI/JMA for the two climate periods: 1979-2008 (present climate) and 2076-2099 (future climate), the numbers of the Korean Peninsula-Approach Typhoon (KPAT) defined by the Korean Meteorological Agency are 41 (1.4 per year) and 46 (1.9 per year) for the present and future climates, respectively. It was found that the typhoon approach increases in the future climate along the Korean Peninsula. In addition, the modeled tracks within the defined region shift from the west coasts to the east coasts due to the climate change. The present study found the highly intensified central pressures (< 920 hPa) appear along the southern and eastern coasts in Korea in the future climate, while those are seen along the western coasts in the present climate.

The extreme distributions of the calculated storm surges are investigated at four different stations along the Korean Peninsula. It was seen from the goodness-of-fit tests that the appropriate probability density functions (PDFs) are the distributions of Generalized Extreme Value (GEV), Frechet and Inverse Gaussian in the future climate. The appropriate PDFs are shifted to the right side along the horizontal axis due to the climate change. These changes are depending on the location. As a consequence, the effect of the climate change on the storm surge should be evaluated in the coastal-scale region and should be taken into account in planning and designing of coastal facilities.

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APPENDIX

The probability density functions employed into the extreme storm surge are as follows.

- The Generalized Extreme Value

$$F(x)=\begin{cases} \exp\left[-\exp\left\{-\dfrac{x-\xi}{\alpha}\right\}\right] & k=0:-\infty<x<\infty \\ & k<0:\xi-\dfrac{\alpha}{k}<x<\infty \\ \exp\left[-\exp\left\{1-k\dfrac{x-\xi}{\alpha}\right\}^{1/k}\right] & k>0:-\infty\le x<\xi+\dfrac{\alpha}{k} \end{cases} \quad \text{(A-1)}$$

where ξ is the location parameter, α is the scale parameter and k is the shape paremeter.

- The Generalized Pareto

$$F(x)=\begin{cases} 1-\exp\left\{-\dfrac{x-\xi}{\alpha}\right\} & k=0:\xi<x<\infty \\ & k<0:\xi<x<\infty \\ 1-\left\{1-k\dfrac{x-\xi}{\alpha}\right\}^{1/k} & 0<k\le 1:\xi\le x<\xi+\dfrac{\alpha}{k} \end{cases} \quad \text{(A-2)}$$

- Fletchet

$$F(x)=\exp\left\{-\left(\frac{\alpha}{x-\xi}\right)^{k}\right\},\xi<x<\infty \quad \text{(A-3)}$$

- Weibull

$$F(x)=1-\exp\left\{\left(\frac{x-\xi}{\alpha}\right)^{k}\right\},\xi<x<\infty \quad \text{(A-4)}$$

- Inverse Gaussian

$$F(x)=\Phi\left\{\sqrt{\frac{k}{x-\xi}}\left(\frac{x-\xi}{\alpha}-1\right)\right\}$$
$$+\Phi\left\{\sqrt{\frac{k}{x-\xi}}\left(\frac{x-\xi}{\alpha}+1\right)\right\}\exp\left(2k/\alpha\right),\xi<x<\infty \qquad \text{(A-5)}$$

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